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**PARTICLE ACCELERATION IN SOLAR FLARES**

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**ABSTRACT**

The most direct signatures of particle acceleration in flares are energetic particles detected in interplanetary space and in the Earth's atmosphere, and gamma rays, neutrons, hard X-rays, and radio emissions produced by the energetic particles in the solar atmosphere. We review the stochastic and shock acceleration theories in flares, and we discuss the implications of observations on particle energy spectra, particle confinement and escape, multiple acceleration phases, particle anisotropies, and solar atmospheric abundances.

**1. INTRODUCTION**

Acceleration of energetic particles is a widespread phenomenon in nature, one that occurs at a variety of sites ranging from the Earth's magnetosphere to distant objects such as supernovae, active galaxies, and quasars. There are, in fact, many explosive phenomena in astrophysics, solar flares among them, in which energetic particles are routinely produced and often contain a large fraction of all the available energy.

It is widely believed [e.g., Syrovatskii, 1981] that solar flares draw their energy from the annihilation of magnetic fields. The rapid energy deposition following the annihilation should be an important source of turbulence and shocks. As proposed by Fermi [1949], charged particles can be accelerated to high energies in repeated reflections from magnetized clouds, or, in the more recent view, from hydromagnetic turbulence and shocks. This mechanism must be important in solar flares where shocks are known to exist and turbulence is expected to be produced by both shocks and other mechanisms. In addition, particles may also be accelerated in the strong electric fields which should accompany the annihilation of magnetic fields.

Indeed, there is ample evidence for particle acceleration in flares. Energetic particles accelerated at the Sun are directly detected in interplanetary space and the neutral radiations (radio emissions, hard X-rays, gamma rays, and neutrons) produced by the accelerated particles in the solar atmosphere are observed with detectors on the ground and in space. These observations provide a variety of information on the properties of the particles, including their energy spectrum, total numbers at the Sun and in interplanetary space, and angular distribution at the Sun. In addition, the measured composition of solar flare particles in interplanetary space [e.g., Breneman and Stone, 1985] and flare gamma ray line spectroscopy [Murphy et al., 1985] provide new information on the chemical composition of the solar atmosphere.

In a previous paper [Forman, Ramaty, and Zweibel, 1986, hereafter FRZ] we have reviewed much of the data, as well as the stochastic, shock, and electric field theories of particle acceleration in solar flares. Several other recent reviews are also available, e.g., Goldman and Smith [1986] on radio emissions, Dennis [1985] on hard X-ray bursts, Hudson [1985] on ions in solar flares, and Lin [1985] on solar electrons in the interplanetary medium. Here we discuss two of the leading acceleration mechanisms, the stochastic Fermi process and diffusive shock acceleration. These mechanisms not only are expected to be important for particle acceleration in flares but also appear to be capable of accounting for many observed solar flare phenomena related to the acceleration of protons and relativistic electrons [Ellison and Ramaty, 1985; Murphy, Dermer and Ramaty, 1987]. We also discuss recent observations of charged particles, gamma rays, and neutrons, with particular focus on the simultaneous observations of flares in all three of these channels.

The present paper is the expanded version of the talk given by one of us (MAF) at Frank McDonald's sixtieth birthday symposium. Frank, through his extensive and pioneering observations of accelerated particles of planetary, solar, interplanetary, and galactic origins, has made fundamental contributions to the understanding of astrophysical particle acceleration. Frank's most recent contribution to solar flare studies, the observation of accelerated particles from two neutron producing flares [McDonald and Van Hollebeke, 1985], is fundamental to the considerations developed and discussed in the present paper.

## 2. ACCELERATION MECHANISMS

### A. Stochastic Acceleration

Processes in turbulent plasmas which cause particles to change their energy in a random way with many increases and decreases in energy lead to stochastic acceleration. In the original stochastic Fermi mechanism [Fermi, 1949], the process was idealized as reflection from randomly moving magnetized clouds. Stochastic acceleration can also result from resonant pitch-angle scattering from Alfvén waves with wavelengths of the order of the particle gyroradius. To accelerate particles these waves must propagate both parallel and antiparallel to the average magnetic field [Skilling, 1975]. Other modes of stochastic acceleration, called magnetic pumping and transit-time damping, occur through interaction with magnetosonic waves whose wavelengths are much longer than the particle gyroradius [Kulsrud and Ferrari, 1971; Melrose, 1980; and Achterberg, 1981]. These modes require additional pitch-angle scattering to keep the particles isotropic. Langmuir (plasma) waves or other electrostatic waves with phase velocities of the order of the particle speed will also accelerate particles stochastically [Melrose, 1980].

When the random energy increments are small compared to the particle energy, stochastic acceleration can be described as diffusion in momentum space characterized by a momentum diffusion coefficient  $D_{pp}$ . Expressions for  $D_{pp}$  for the various processes mentioned above were summarized in FRZ. Stochastic-acceleration spectra can be obtained from these  $D_{pp}$ 's by solving a transport equation [see FRZ and Droge and Schlickeiser, 1986] which takes

into account the injection of the particles, diffusion in momentum space, non-diffusive energy changes (e.g., ionization losses, and nuclear collisions), and escape from the acceleration region. Several of the published stochastic-acceleration spectra are given in FRZ.

Here we discuss the simple model of acceleration by hard sphere scattering which has been applied extensively to both solar flare particle observations in interplanetary space [McGuire and von Rosenvinge, 1984] and gamma ray and neutron production models at the Sun [Murphy and Ramaty, 1984; Murphy, Dermer, and Ramaty, 1987]. In this treatment [Ramaty, 1979; FRZ] the scattering mean free path is assumed to be independent of particle energy and species, the acceleration region is characterized by a constant escape time and all additional losses are ignored. With a steady source of  $q$  particles  $\text{cm}^{-3} \text{s}^{-1}$  at an injection momentum  $p_0$ , the steady state particle density in phase space as a function of particle momentum  $p$  is given by:

$$f = 6 q / (4 \pi p_0^2 m c \alpha) (p_0/p) \cdot I_2(2(3p_0/(m c \alpha T))^{1/2}) K_2(2(3p/(m c \alpha T))^{1/2}), \quad (1)$$

if both  $p$  and  $p_0$  are nonrelativistic, and by:

$$f = q / (4 \pi p_0^3 \alpha (1 + 4/(3 \alpha T))^{1/2}) \cdot (p/p_0)^{-3/2 - \sqrt{(9/4 + 3/\alpha T)}} , \quad (2)$$

when both  $p$  and  $p_0$  are ultrarelativistic. Here  $m$  is particle mass,  $p$  particle momentum,  $T$  the escape time from the acceleration region, and  $\alpha = (\delta V)^2 / (\lambda c)$  where  $(\delta V)^2$  is the mean square velocity of the scatterers and  $\lambda$  the diffusion mean free path in momentum space. The combination of parameters  $\alpha T$  characterizes the shape of the spectrum such that a larger value of  $\alpha T$  corresponds to a harder spectrum. The phase space density  $f$  is related to the differential particle density,  $N(E)$ , or the differential particle flux,  $J(E)$ ,  $N(E) = J(E)/v = A p^2 f/v$ , where  $E$  is energy per nucleon,  $A$  is particle mass number, and  $v$  particle velocity. In both Equations (1) and (2)  $p$  must be greater

than  $p_0$ . For  $p < p_0$ , the arguments of  $I_2$  and  $K_2$  in Equation (1) are interchanged, and the minus sign in front of the square root in the exponent in Equation (2) is changed to a plus sign.

The nonrelativistic expression, Equation (1), can be used to fit solar flare accelerated ion spectra up to about 100 MeV/nucleon. Such fits are discussed in Section 3. The ultrarelativistic expression, Equation (2), could be used to fit electron spectra above about 1 MeV. But if  $\alpha T$  is rigidity independent, the values of  $\alpha T$  that fit the proton spectra produce ultrarelativistic electron spectra which are much steeper than those observed [e.g., Ramaty, 1979]. Clearly, a complete stochastic acceleration model should take into account the rigidity dependence of  $\alpha T$ , but no attempts have yet been made (see FRZ) to compare the theory with data in detail.

A very important question in all particle acceleration theories, including stochastic acceleration, is that of injection. We first note that the basic concept of stochastic acceleration assumes that the energy changes are small compared with the particle energy and therefore the particle velocity must be much greater than  $\delta V$ . Furthermore, for resonant scattering, ions must have  $v > V_A$  to scatter from Alfvén waves and electrons must have  $v > 43V_A$  to scatter from whistlers [Melrose, 1974]. An additional injection condition is set by the requirement that the systematic acceleration rate due to diffusion in momentum space be larger than the ionization and Coulomb energy loss rates of the particles. A detailed comparison of these rates was given in FRZ.

The acceleration time in stochastic acceleration can be studied from the time dependent solutions of the transport equation. The relevant parameters are  $\delta V$  and  $\lambda$ . If we set  $\delta V = V_A$ , then a typical value is  $\delta V = 1000$  km/sec, corresponding to a magnetic field of 100 gauss and an electron density of  $5 \times 10^{10} \text{ cm}^{-3}$ . The diffusion mean free path should be at least as large as the particles gyroradius. Taking  $\lambda$  to be 100 times the gyroradius of a 20 MeV proton, we obtain  $\lambda = 7 \times 10^5$  cm. Then the acceleration parameter  $\alpha \cong 0.5$ . For this  $\alpha$ , the time dependent solutions of the transport equation obtained [Ramaty, 1979; FRZ] for impulsive injection and perfect trapping ( $T \rightarrow \infty$ ) imply that a significant number of protons are accelerated to tens of MeV in less than 1 sec. In general, a time of the order  $1/\alpha$  is required to accelerate particles to relativistic energies.

## B. Shock Acceleration

Solar flare shocks propagate upward through the solar corona at speeds of about 500 to 2000 km/sec, as indicated by Type II radio bursts [e.g., Goldman and Smith, 1986] and laterally through the chromosphere where they are seen as Moreton waves [Uchida, 1974]. The occurrence of solar energetic particles in space is strongly correlated with flares having Type II bursts [Svestka and Fritzova, 1974]. Flare shocks, corotating shocks, and planetary bow shocks are observed to accelerate particles in interplanetary space (see references in FRZ). A flare shock can transport particles in an energy independent manner through the corona until they escape onto open field lines. Shock acceleration has been reviewed by Toptygin [1980] and Axford [1982] and applied to solar flares by Achterberg and Norman [1980], Decker, Pesses, and Armstrong [1981], Ellison and Ramaty [1985], and Lee and Ryan [1986].

There are basically two types of shock acceleration: scatter-free, in which particles gain energy by reflection in a single shock encounter [Sonnerup, 1973; Armstrong, Pesses, and Decker, 1985; references in FRZ] and diffusive, in which particles gain energy by repeated scattering between the converging plasmas on either side of the shock [e.g., Axford, Leer, and Skadron, 1977; Axford, 1982 and; Forman and Webb, 1985]. The scatter-free mechanism can enhance the particle energy by about an order of magnitude if the shock is nearly perpendicular (i.e., the magnetic field is nearly perpendicular to the shock normal), but in that case only particles with speeds which are already much greater than the shock speed can be reflected. Further acceleration, however, requires multiple reflections. These are possible if there is particle scattering in the fluid flow or if the particles are trapped between converging shocks in a flare loop [Wentzel, 1965; Bai et al., 1983].

Acceleration by diffusive scattering across the shock is a first order Fermi process, in the sense that every shock crossing results in an energy gain. It is in principle more efficient than stochastic acceleration because it derives energy directly from the compression of the flow at the shock. For this mechanism to be effective, there must be adequate particle scattering both upstream and downstream of the shock. The passage of the shock is expected to generate turbulence downstream which will scatter the particles. Scattering upstream, however, is more problematic [Holman, Ionson, and Scott,

1979]. Observations [Tsurutani and Rodriquez, 1981] of interplanetary shocks and planetary bow shocks show that when they are nearly parallel there is a very turbulent foreshock region capable of scattering particles. Such a region could be produced by the accelerated particles themselves [Achterberg and Norman, 1980; Lee, 1982].

In the simplest example of diffusive shock acceleration at a planar shock where the only losses are due to convection of the particles away from the shock downstream, the energetic particle density in phase space is given by a power law in momentum,  $f \sim p^{-\sigma}$ , where  $\sigma = 3V/\Delta V$ ,  $V$  is the shock speed and  $\Delta V$  the discontinuity in the plasma speed at the shock. In terms of the shock compression ratio,  $r$ ,  $\sigma = 3r/(r-1)$ . For a strong shock in a nonrelativistic fluid  $r = 4$  and hence  $f \sim p^{-4}$ . For weaker shocks,  $4 > r > 1$  and the power law is steeper. The momentum power law  $p^{-\sigma}$  implies [Ellison and Ramaty, 1985] that differential flux as a function of energy per nucleon,  $J(E)$ , has an energy dependent spectral index which approaches  $s = (r+2)/(r-1)$  in the ultrarelativistic regime and  $s/2$  in the nonrelativistic regime.

A variety of effects truncate the power law behavior of shock-accelerated spectra at high energies. The effects that have been considered specifically are adiabatic deceleration [Lee and Ryan, 1986], shock lifetimes comparable to particle acceleration times [Forman, 1981] and shock sizes comparable to particle diffusion lengths [e.g., Ellison, 1984]. These effects all produce spectra that turn over at high energies when the diffusion coefficient increases with momentum. The derivation of the exact forms of these turnovers generally requires numerical treatments. In many cases, however, they can be approximated by exponentials [e.g., Ellison and Ramaty, 1985],

$$f_i(p) \sim p^{-\sigma} \exp(-E/E_{oi}), \quad (3)$$

where  $f_i$  is the phase space density of particles of species  $i$ , and  $E_{oi}$  is the turn-over kinetic energy for species  $i$ . In the case of particle escape at an escape boundary at a given distance from the shock,  $E_{oi}$  depends on the distance to this boundary and the diffusion coefficient. If the diffusion mean free path

is proportional to particle gyroradius, the turnover energies of the various species are related by:

$$v(E_{0i}) R(E_{0i}) = v(E_{0p}) R(E_{0p}), \quad (4)$$

where  $R$  is particle rigidity,  $E_{0p}$  is the proton turnover kinetic energy, and  $E_{0i}$  is energy per nucleon for nuclei and energy for electrons. Equation (3) can be used to fit both ion and electron spectra. We present such a fit in the next section.

As for stochastic acceleration, and for shock acceleration as well, the question of injection is very important. Ionization and Coulomb energy losses to the ambient medium have the same role in determining injection conditions in shock acceleration as they do in stochastic acceleration. In addition, for diffusive shock acceleration, particles downstream must have sufficient velocity to overtake the shock. This is at least  $(V - \Delta V)$  directed towards the shock, and increases as  $(\cos \psi)^{-2}$ , where  $\psi$  is the angle between the downstream field and the shock normal. The velocity  $V - \Delta V$  is at least as great as  $V_A$  or  $\Delta V$ , and with the additional  $(\cos \psi)^{-2}$  factor, the threshold for shock acceleration could be higher than for stochastic acceleration.

Another injection condition is set by the finite width of the shock which could depend on many parameters including the pressure of the accelerated particles. When this pressure is taken into account [Axford, Leer, and Skadron, 1977; references in FRZ] all or part of the velocity change  $\Delta V$  is smoothed out over a length scale  $\sim \bar{k}/V$ , where  $\bar{k}$  is the diffusion coefficient of the energetic particles averaged over their energy spectrum. This smoothing could affect the composition of the accelerated particles [Eichler, 1979]. Drury, Axford, and Summers [1982] show analytically that when  $k$  is independent of energy, the smoothing causes the dominant accelerated species (i.e., protons) to have a steeper spectrum than in the case of an infinitely thin shock. Minor species which are only partially stripped could have larger diffusion coefficients than the protons if the diffusion mean free path is rigidity dependent, and therefore for them  $k > \bar{k}$ . Drury, Axford, and Summers [1982] show that the spectrum of such minor species is flatter than for protons and approaches that of an infinitely thin shock.



The mean rate of energy gain in shock acceleration is (see FRZ):

$$dE/dt = 3/4 (V \Delta V) (p/\lambda). \quad (5)$$

Ellison and Ramaty [1985] have shown that if  $\lambda$  is proportional to gyroradius, the acceleration time for both protons and electrons is:

$$t_a \cong 2 \times 10^{-4} f (E - E_{inj}) / ((B/100 \text{ gauss})(V \Delta V/10^6 \text{ km}^2/\text{sec}^2)), \quad (6)$$

where  $t_a$  is in sec,  $E$  and  $E_{inj}$  are the final and injection energies in MeV, and  $f$  is the ratio of  $\lambda$  to the gyroradius. It is expected that  $f$  is much greater than unity. For  $f = 100$ ,  $B = 100$  gauss and  $V = \Delta V = 10^3$  km/sec, the acceleration time to 20 MeV is  $\sim 0.4$  sec. We note that the acceleration time is the same for protons and electrons, a result which follows from the assumed linear dependence of the mean free path on gyroradius.

### 3. OBSERVATIONS AND THEIR INTERPRETATIONS

We discuss the following: (1) energy spectra, (2) the trapping and escape of the particles and the related problem of multiple acceleration phases, (3) angular distributions at the Sun, and (4) abundance determinations from energetic particle and gamma ray observations.

#### A. Energy Spectra

The energy spectrum of accelerated particles is perhaps the most important diagnostic of acceleration mechanisms. Information on energy spectra is obtained from both the charged particles observed in interplanetary space, and the gamma ray and neutron data. The interplanetary observations provide information on the energy spectrum of the particles which escape from the Sun.

As indicated by upper limits on  $^2\text{H}$ ,  $^3\text{H}$ , Li, Be, and B [McGuire, von Rosen-vinge, and McDonald, 1979], the amount of matter traversed by the escaping particles ( $< 0.1 \text{ g/cm}^{-3}$ ) is generally insufficient for the production of the observed gamma rays [Ramaty, 1986]. Gamma rays and neutrons are produced by the particles which slow down and thermalize in the solar atmosphere.

Observations of these neutral emissions, therefore, provide information on the particles which remain trapped at the Sun.

The energy spectra obtained from charged particle observations have been reviewed by McGuire and von Rosenvinge [1984]. In determining spectra from such observations the effects of coronal and interplanetary transport must be minimized. It was shown [Van Hollebeke, MaSung, and McDonald, 1975] that this can be achieved by considering only particle events from flares that are well connected magnetically to the observing spacecraft and by constructing the energy spectra at times of maximum intensity at each energy. Using this technique, McGuire, von Rosenvinge, and McDonald [1981] and McGuire and von Rosenvinge [1984] showed that over the broad energy range (from about 1 to 400 MeV) proton spectra can be fit with the Bessel function spectra expected from stochastic acceleration [Equation (1)] with values of  $\alpha T$  between 0.015 and 0.035. But as emphasized in FRZ, energy spectra obtained from shock acceleration could also fit these data.

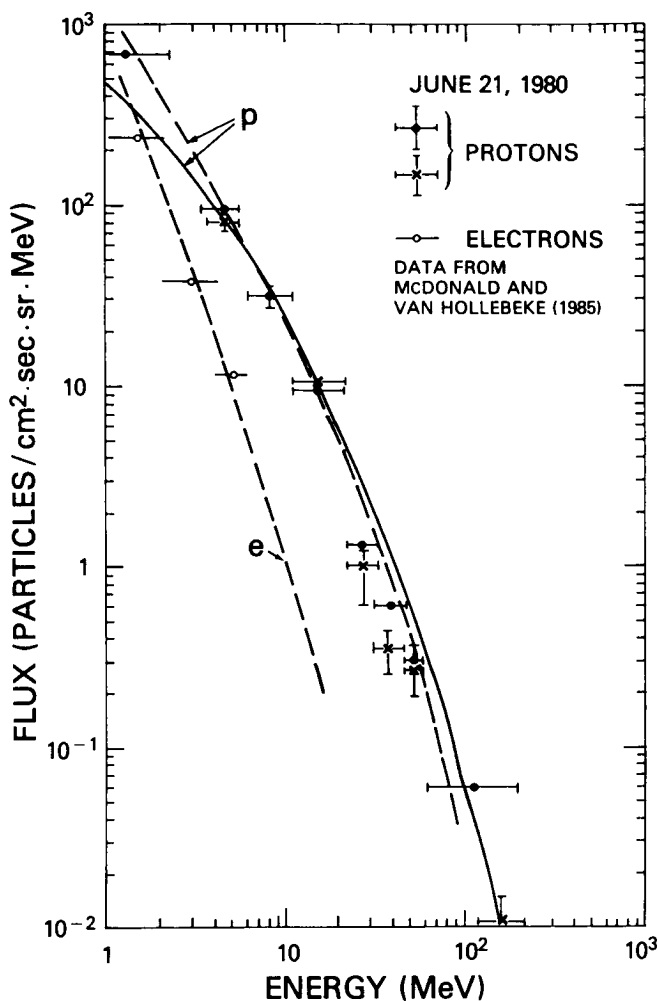
Proton spectra have been determined from gamma ray and neutron observations using three different techniques [Murphy and Ramaty, 1984; Murphy, Dermer, and Ramaty, 1987]. The first one considers the ratio of the fluence in excess of a power law in the 4-7 MeV range to the fluence in the 2.223 MeV line. This excess is due to nuclear line emissions. The second technique uses observed neutron spectra which depend on the spectrum of the protons which produce the neutrons; and the third is based on the ratio of the 4-7 nuclear excess to the pion decay emission at photon energies  $> 10$  MeV. The first technique is sensitive to the spectrum in the 10 - 100 MeV range, the second probes the spectrum in the 50 MeV - several GeV range and the third is sensitive to the ratio of the number of particles in the 10 - 100 MeV range to the number above the pion production threshold (few hundreds MeV).

When analyzed in terms of the Bessel function of Equation (1), the 4-7 MeV to the 2.223 MeV line ratios for 15 flares yielded values of  $\alpha T$  in the range from 0.014 to 0.038 [Murphy and Ramaty, 1984; Hua and Lingenfelter, 1987a]. This range is essentially the same as that obtained from the interplanetary charged particle data. However, the implications of this overlap are not clear because most of the particle events correspond to a different set of flares than the one used to derive the gamma ray results.

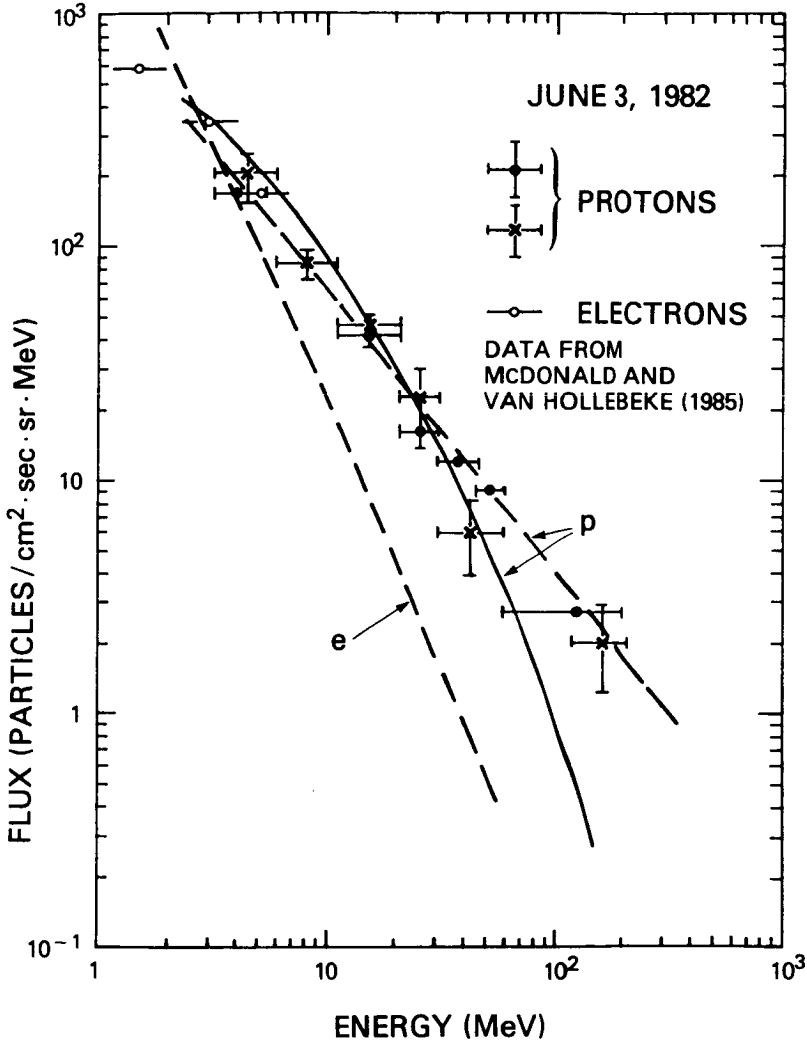
There are, in fact, only three flares for which energy spectra have been determined simultaneously from gamma ray and charged particle data: June 7, 1980; June 21, 1980; and June 3, 1982. For the June 7 flare, the 4-7 MeV to 2.223 MeV ratio yields  $\alpha T = 0.021 \pm 0.003$  [Murphy and Ramaty, 1984; Hua and Lingenfelter, 1987a] and the charged particle data yield  $\alpha T = 0.013$  [McGuire and von Rosenvinge, 1985]. For the June 21 flare, the 4-7 MeV to 2.223 MeV ratio yields  $\alpha T = 0.022 \pm 0.007$  [Hua and Lingenfelter, 1987a] and the charged particle data yield  $\alpha T \cong 0.025$  [Murphy, Dermer, and Ramaty, 1987] using the data of McDonald and Van Hollebeke [1985] shown in Figure 1. For the June 21 flare  $\alpha T$  was also determined [Murphy and Ramaty, 1984] from neutron observations [Chupp et al., 1982] yielding  $\alpha T \cong 0.025$ . We see that for both the June 7 and June 21 flares the spectrum of the particles which escaped from the Sun could have been similar to the spectrum of the particles which slowed down and thermalized in solar atmosphere. It is possible that for these flares a common acceleration mechanism operating at a common acceleration site is responsible for both particle populations.

The interplanetary proton and electron spectra from the June 3, 1982 flare [McDonald and Van Hollebeke, 1985] are shown in Figure 2 [from Murphy, Dermer, and Ramaty, 1987]. As can be seen, a power law fits the proton spectrum better than does a Bessel function. This power law is given by Equation (3) with  $s = 2.4$  ( $\sigma = 4.4$ ) and  $E_{op} \gg 300$  MeV. The gamma ray data from this flare, however, cannot be reproduced with a single, time independent, proton spectrum [Murphy, Dermer, and Ramaty, 1987]. Early in the flare (for about 100 sec) the proton spectrum can be fit with a Bessel function with  $\alpha T \cong 0.04$ , but later in the event the observed ratio of the 4-7 MeV nuclear excess [Prince et al., 1983; Chupp et al., 1987] to the emission from the decay of pions [Forrest et al., 1985, 1987] implies that the spectrum must harden. At these later times the spectrum is consistent with the proton spectrum observed in interplanetary space ( $s = 2.4$  and  $E_{op} > 300$  MeV).

The inferred hardening of the proton spectrum suggests that not all the particles accelerated in the June 3 flare had a common origin. Murphy, Dermer, and Ramaty [1987] show that a wide variety of data from the June 3 flare (pion decay emission, nuclear deexcitation lines, the 2.223 MeV and 0.511



*Figure 1. Interplanetary proton and electron observations [McDonald and Van Hollebeke, 1985] of the June 21, 1980 flare. The solid curve corresponds to a stochastic-acceleration spectrum with  $\alpha T = 0.025$ , and the dashed curves correspond to shock-acceleration spectra with  $s = 3.3$  and  $E_{op} = 30$  MeV for the protons and  $E_{oe} = 59$  MeV for the electrons.*



*Figure 2. Interplanetary proton and electron observations [McDonald and Van Hollebeke, 1985] of the June 3, 1982 flare. The solid curve corresponds to a stochastic-acceleration spectrum with  $\alpha T = 0.04$ , and the dashed curves correspond to shock-acceleration spectra with  $s = 2.4$  and  $E_{0p}$  and  $E_{0e}$  tending to infinity.*

MeV lines, neutrons and interplanetary charged particles) can be explained by a model which incorporates two distinct particle populations with different acceleration histories and different but time independent energy spectra. They suggest that the softer proton spectrum is accelerated early in the flare by the first of two acceleration phases, while later in the flare second phase acceleration produces a much harder spectrum. We shall discuss these multiple acceleration phases in the next subsection, but before that we will comment on the maximum energy of particles accelerated in flares.

As just mentioned, the interplanetary proton spectrum of the June 3, 1982 flare was exceptionally hard, but these observations determined the proton spectrum only up to  $\sim 200$  MeV. The ground-based neutron observations from this flare [Debrunner et al., 1983], which are very sensitive to protons of GeV energies, set an upper limit,  $E_{op} < 3$  GeV [Murphy, Dermer, and Ramaty, 1987]. The highest energy particles from flares have been seen with ground-based detectors. These show that the interplanetary proton spectrum from solar flares occasionally extends to energies  $> 10$  GeV [Debrunner et al., 1984].

## B. Trapping and Escape of Particles and Multiple Acceleration Phases

With a few exceptions (the flares of August 4, 1972 and June 3, 1982), the number of protons deduced from gamma ray and neutron observations exceeds by at least an order of magnitude the number obtained from interplanetary observations of the same flares. This implies that the gamma rays and neutrons are produced by particles accelerated in and confined to closed magnetic configurations, probably magnetic loops. On the other hand, there are many flares which produce large fluxes of interplanetary particles without producing detectable gamma rays or neutrons. The flare of December 9, 1981 is an example [Cliver et al., 1983]. The number of escaping particles from this flare exceeds the upper limit set [Vlahos et al., 1987] by gamma ray observation by a factor of 5. These particles are most likely accelerated at coronal sites with ready access to interplanetary space.

These results are consistent with the two phase acceleration model suggested originally by Wild, Smerd, and Weiss [1963]. Recently Cane, McGuire, and von Rosenvinge [1986] have related the two acceleration phases to two classes

of solar flare particle events which can be distinguished by a variety of signatures including the duration of their associated soft X-ray emission [Pallavicini, Serio, and Vaiana, 1977]. The first class, characterized by short duration impulsive events, is probably due to impulsive energy release in compact source regions relatively low in the corona. The second class, characterized by longer duration soft X-ray emission, corresponds to energy release in extended regions high in the corona. It is reasonable to associate the bulk of the gamma ray flares (including the June 7, 1980 and June 21, 1980 flares for which only a small fraction of the protons escaped from the Sun) with the first class or the first phase, and the interplanetary proton events which do not show detectable gamma rays (e.g., the December 9, 1981 flare) with the second class or phase. A similar classification has also been proposed recently by Bai [1986].

Of all flares, only the June 3, 1982 flare produced observable gamma ray emission which can be associated with second phase acceleration. As in other gamma ray flares, this flare also produced nuclear line emission and neutron capture radiation [Prince et al., 1983; Chupp et al., 1987]. These emissions are typical of first phase acceleration [Murphy, Dermer, and Ramaty, 1987]. But the June 3 flare also produced emission from the decay of pions [Forrest et al., 1987] and the time profile of the observed pion decay emission strongly suggests second phase acceleration [Ramaty, Murphy, and Dermer, 1987]. The number of escaping particles from this flare was smaller by about an order of magnitude than the number deduced from the gamma ray and neutron data in the first phase and exceeded by a factor of about 50 the number deduced from the pion decay gamma rays in the second phase. In addition, as discussed above, the spectrum of the escaping particles is much more consistent with the spectrum of the second phase particles than with that of the first phase ones. These results suggest that during its first phase the June 3 flare was similar to the other gamma ray flares in which the bulk of the interacting particles remained trapped and thermalized at the Sun. During the second phase of this flare, the bulk of the particles escaped. This phase of the June 3 flare resembles the flares which produce interplanetary particles without detectable gamma rays and neutrons. Second phase gamma rays were seen from the June 3 flare only because of its very hard proton spectrum which led to efficient pion production.

### C. Energetic Particle Anisotropies in the Solar Atmosphere

The observations that continuum gamma ray emission is seen preferentially from flares close to the solar limb [Rieger et al., 1983; Vestrand et al., 1987] suggest that the angular distribution of the relativistic electrons in the region where the gamma rays are produced is anisotropic. It was suggested that this limb brightening could be due to an electron distribution that at injection was isotropic in the downward hemisphere [towards the photosphere, Petrosian, 1985], and by electron distributions in the interaction region which were peaked at directions either parallel or perpendicular (downward) to the photosphere [Dermer and Ramaty, 1986].

The angular distribution of the protons in the gamma ray production region can be studied by comparing the 2.223 MeV line, which is produced by neutrons moving downward into the photosphere, with the neutron flux observed near Earth. A recent study [Hua and Lingenfelter, 1987b] indicates that both an isotropic ( $4\pi$ ) proton distribution and a distribution peaking at directions parallel to the photosphere are consistent with the data, but a distribution which is isotropic in only the downward hemisphere is not. This result, coupled with those on relativistic electrons, suggests that the gamma rays are probably produced by a mirroring distribution peaking at directions parallel to the photosphere.

### D. Solar Elemental Abundances

The observation of energetic particles escaping from the Sun and gamma ray lines from solar flares have provided two new techniques for determining elemental abundances in the solar atmosphere. The elemental composition of the energetic particle depends on the composition of the ambient medium from which these particles are accelerated, but the injection and acceleration processes are expected to modify the composition significantly. Gamma ray line intensities are directly proportional to the abundance of elements in the ambient solar atmosphere, but so far the gamma ray spectrum of only one flare was analyzed in sufficient detail to determine abundances.



Nuclei heavier than He in solar energetic particles were first detected by Fichtel and Guss [1961] and since then many measurements of such particles have been made (see references in FRZ). The observed solar energetic particle composition is highly variable. The most dramatic departure of a solar energetic particle abundance from its photospheric value is that of  $^3\text{He}$  [Garrard, Stone, and Vogt, 1973]. Here very large enhancements are observed in the  $^3\text{He}/^4\text{He}$  ratio above its likely photospheric value [see Kocharov and Kocharov, 1984 for review]. These enhancements are probably caused by resonant heating of  $^3\text{He}$  in the ambient atmosphere which could lead to the preferential accelerations of  $^3\text{He}$  [Fisk, 1978; Kocharov and Kocharov, 1978]. It has been shown recently [Reames, von Rosenvinge, and Lin, 1985] that the preferential acceleration of  $^3\text{He}$  is most likely a first phase phenomenon.

Observations of the 2.223 MeV line from solar flares have been used to determine the photospheric abundance of  $^3\text{He}$ . It was shown by Wang and Ramaty [1974] that the photospheric  $^3\text{He}$  is an important neutron sink and therefore the observed 2.223 MeV line, which results from neutron capture on  $^1\text{H}$ , can set limits on the photospheric  $^3\text{He}$  abundance. Recently, Hua and Lingenfelter [1987c] used the detailed June 3, 1982 observations of the 2.223 MeV line [Prince et al., 1983] to determine the  $^3\text{He}$  abundance. They obtained  $^3\text{He}/\text{H} = (2.3 \pm 1.2) \times 10^{-5}$ .

It would appear that the large variations of the observed composition of the solar energetic solar particles would preclude the determination of abundances in the ambient medium. Nonetheless, it has been suggested [Meyer, 1985a] that for non  $^3\text{He}$  rich flares (for which the abundance variations are relatively small) the acceleration and injection effects could be separated from effects related to the ambient medium composition. In particular, it has been shown [Breneman and Stone, 1985] that the ratio of the abundance of elements observed in individual flares to the mean abundance (determined by averaging abundances of several flares) is a monotonic function,  $(Q/M)^x$ , where  $Q$  and  $M$  are ionic charge and mass, and  $x$  varies from flare to flare. These mean abundances could be similar to those of the ambient medium.

In Table 1 we show abundances derived from various sources. The local galactic (LG) set [Meyer, 1985b] is thought to represent photospheric abundances,

TABLE 1  
Elemental Abundances

Element	Local Galactic <sup>1</sup>	Corona <sup>1</sup>	SEP <sup>2</sup>	Gamma Rays <sup>3</sup>
C	1260.00 (1.26)	600.00 (3.00)	271.00+-26.00	288.00+-50.00
N	225.00 (1.41)	100.00 (1.70)	77.50+- 5.20	117.00+-91.00
O	2250.00 (1.25)	630.00 (1.60)	623.00+-35.00	422.00+-62.00
Ne	325.00 (1.50)	90.00 (1.60)	88.70+- 8.70	199.00+-27.00
Na	5.50 (1.18)	7.00 (1.70)	7.33+- 0.70	- - - -
Mg	105.00 (1.03)	95.00 (1.30)	120.60+- 6.20	68.00+-25.00
Al	8.40 (1.05)	7.00 (1.70)	8.74+- 0.42	- - - -
Si	100.00 (1.03)	100.00 (1.30)	100.00	100.00+-28.00
P	0.94 (1.24)	- - - -	0.46+- 0.07	- - - -
S	43.00 (1.36)	22.00 (1.70)	22.20+- 0.75	48.00+-83.00
Cl	0.47 (1.60)	- - - -	0.21+- 0.07	- - - -
Ar	10.70 (1.50)	5.40 (1.80)	2.07+- 0.33	- - - -
K	0.34 (1.14)	- - - -	0.33+- 0.15	- - - -
Ca	6.20 (1.14)	7.50 (1.60)	6.80+- 1.10	17.00+-15.00
Ti	0.27 (1.16)	- - - -	0.38+- 0.11	- - - -
Cr	1.29 (1.10)	- - - -	1.43+- 0.27	
Mn	0.77 (1.24)	- - - -	0.52+- 0.25	
Fe	88.00 (1.07)	100.00 (1.50)	95.90+-10.00	76.00+-18.00
Ni	4.80 (1.13)	5.50 (1.70)	3.38+- 0.50	- - - -
Zn	0.10 (1.22)	- - - -	0.11+-0.05	- - - -

1. Meyer (1985b)

2. Breneman and Stone (1985)

3. Murphy et al. (1985)

even though the Ne abundance has not yet been measured in the photosphere. The coronal (COR) set, based on spectroscopic observations of the corona, is also from Meyer [1985b]. The mean solar energetic particle abundances (SEP) are from Breneman and Stone [1985]. The gamma ray (GR) set is from Murphy et al. [1985].

To compare these abundances, we have renormalized each pair of sets using multiplicative factors determined by minimizing  $\chi^2$ . The ratios of elemental abundances for each pair are shown in Table 2; together with the number of degrees of freedom,  $n$ ; the value of the reduced  $\chi^2$ ,  $\chi_n^2$ ; and the corresponding probability. Here the elements are ordered by decreasing first ionization potential. As can be seen, it is very improbable that the LG and SEP sets are drawn from the same underlying population. In particular, the SEP to LG ratios for elements with high ionization potential are lower than the ratios for elements with low ionization potential. A similar suppression has been found in the coronal abundances relative to the local galactic abundances (see the COR/LG ratios), although here the difference is much less significant. As we have argued above, and as suggested by charge state measurements [Gloeckler, 1985], the solar energetic particles are probably accelerated in the corona. The SEP abundance set could therefore represent coronal abundances. The differences between coronal and photospheric abundances could be caused by charge dependent mass transport from the photosphere to the corona. Since the photosphere is collisionally ionized at a relatively low temperature, the transport could be less efficient for elements with high ionization potential, leading to suppressed abundances for such elements.

The gamma ray set probably represents chromospheric abundances in a flare loop [Murphy and Ramaty, 1984]. As for the SEP/LG ratios, the GR/LG ratios for O and C are lower than the ratios for Mg, Si, and Fe. The ionization potentials of C and O are higher than those of Mg, Si, and Fe. The suppression of the C and O abundances could also be caused by charge dependent transport, from the photosphere to the chromosphere in this case. However, if the Ne abundance in the photosphere (where it cannot be measured) is the same as in the local galactic set, then the difference between the chromospheric and photospheric abundances must be due to additional processes, because correlation with first ionization potential alone would

TABLE 2

Ratios of elemental abundances for the six combinations of the data sets of Table 1. Also shown are the degrees of freedom,  $n$ , the minimal reduced  $\chi^2$  and the corresponding probability,  $P(X)$ , for each set of ratios. The elements are ordered by decreasing first ionization potentials.

Element	SEP/LG	GR/LG	SEP/COR	GR/COR	GR/SEP	COR/LG
Ne	0.27 $\pm$ 0.14	0.80 $\pm$ 0.41	0.93 $\pm$ 0.57	1.84 $\pm$ 1.13	2.17 $\pm$ 0.36	0.32 $\pm$ 0.25
Ar	0.19 $\pm$ 0.10	- - -	0.36 $\pm$ 0.30	- - -	- - -	0.58 $\pm$ 0.55
N	0.34 $\pm$ 0.14	0.68 $\pm$ 0.59	0.73 $\pm$ 0.52	0.97 $\pm$ 1.02	1.46 $\pm$ 1.14	0.51 $\pm$ 0.41
O	0.27 $\pm$ 0.07	0.24 $\pm$ 0.07	0.93 $\pm$ 0.56	0.56 $\pm$ 0.34	0.66 $\pm$ 0.10	0.32 $\pm$ 0.21
Cl	0.42 $\pm$ 0.29	- - -	- - -	- - -	- - -	- - -
C	0.21 $\pm$ 0.06	0.30 $\pm$ 0.09	0.43 $\pm$ 0.85	0.40 $\pm$ 0.80	1.03 $\pm$ 0.20	0.55 $\pm$ 1.10
P	0.48 $\pm$ 0.13	- - -	- - -	- - -	- - -	- - -
S	0.50 $\pm$ 0.18	1.45 $\pm$ 2.56	0.95 $\pm$ 0.67	1.81 $\pm$ 3.39	2.09 $\pm$ 3.62	0.59 $\pm$ 0.46
Zn	1.05 $\pm$ 0.57	- - -	- - -	- - -	- - -	- - -
Si	0.97 $\pm$ 0.03	1.30 $\pm$ 0.37	0.95 $\pm$ 0.28	0.83 $\pm$ 0.34	0.97 $\pm$ 0.27	1.15 $\pm$ 0.35
Fe	1.06 $\pm$ 0.13	1.12 $\pm$ 0.28	0.91 $\pm$ 0.46	0.63 $\pm$ 0.35	0.77 $\pm$ 0.20	1.30 $\pm$ 0.66
Mg	1.12 $\pm$ 0.07	0.84 $\pm$ 0.31	1.20 $\pm$ 0.37	0.60 $\pm$ 0.28	0.55 $\pm$ 0.20	1.04 $\pm$ 0.31
Ni	0.69 $\pm$ 0.13	- - -	0.58 $\pm$ 0.42	- - -	- - -	1.32 $\pm$ 0.94
Mn	0.66 $\pm$ 0.35	- - -	- - -	- - -	- - -	- - -
Ti	1.37 $\pm$ 0.45	- - -	- - -	- - -	- - -	- - -
Cr	1.08 $\pm$ 0.23	- - -	- - -	- - -	- - -	- - -
Ca	1.07 $\pm$ 0.23	3.56 $\pm$ 3.18	0.86 $\pm$ 0.53	1.89 $\pm$ 2.01	2.42 $\pm$ 2.17	1.39 $\pm$ 0.86
Al	1.01 $\pm$ 0.07	- - -	1.18 $\pm$ 0.83	- - -	- - -	0.96 $\pm$ 0.67
Na	1.30 $\pm$ 0.26	- - -	0.99 $\pm$ 0.70	- - -	- - -	1.46 $\pm$ 1.06
K	0.94 $\pm$ 0.45	- - -	- - -	- - -	- - -	- - -
$n$	19	8	12	8	8	12
$\chi^2$ $X(n)$	2.29	2.47	0.15	0.51	3.61	0.85
$P$	$1.1 \times 10^{-3}$	$1.1 \times 10^{-2}$	$>0.99$	0.85	$<10^{-3}$	0.6

predict a lower Ne abundance than the one obtained from the gamma ray studies.

Also shown in Table 2 are ratios of the gamma ray set to the SEP and coronal sets, and the ratios of the coronal set to the local galactic set. The difference between the GR and SEP sets is significant. In addition to the different Ne abundances, we also note that Mg in the GR set is significantly lower than in the SEP set (see also Table 1). There is no simple interpretation for this result. Clearly, the effects of injection and acceleration on the mean SEP abundances are not fully understood. Also, gamma ray data from more flares are needed to establish the constancy or variability of the abundances derived from gamma ray spectroscopy.

Elemental compositions have also been studied for  $^3\text{He}$  rich flares. Mason et al. [1986] found that the heavy ion enrichments seen in these flares are uncorrelated with the  $^3\text{He}$  enrichment. As pointed out above, the  $^3\text{He}$  enrichment is most likely due to preferential heating and acceleration. Mason et al. [1986] suggest that the heavy ion enrichments seen in  $^3\text{He}$  flares are caused by enrichments in the ambient coronal composition.

#### 4. SUMMARY

That particle acceleration plays a dominant role in the physics of solar flares has been known for some time. In the present paper we have emphasized phenomena related to the acceleration of ions and relativistic electrons. We treated the presently best understood acceleration mechanisms, stochastic acceleration, and shock acceleration. We presented recent charged particle, gamma ray, and neutron observations, and we discussed their implications. These observations are highly complementary. The gamma rays and neutrons provide information on the particles which thermalize in the solar atmosphere, while the charged particles observations provide a direct sample of the escaping particles. The combination of information on the escaping and trapped particle populations strongly suggests the existence of multiple acceleration phases, which could be the manifestation of multiple acceleration sites, times, and perhaps even mechanisms.

Particles accelerated in solar flares also provide information on elemental abundances in the solar atmosphere. This information is obtained by measuring the composition of the escaping particles, by observing the gamma ray lines which are produced from ambient nuclei excited by the accelerated particles, and by studying the 2.223 MeV line which gives information on the  $^3\text{He}$  in the photosphere. Abundance variations in the chromosphere and corona are suggested by these observations.

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